EuroSTRATAFORM: Off-shelf Sediment Transport Processes in the Gulf of Lions

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LONG-TERM GOAL

The long-term goal of the sediment transport and accumulation component of Euro-STRATAFORM is to link sediment-transport processes to the formation and preservation of event beds in sediment deposits. Specifically we would like to

1) investigate the range of processes responsible for along- and off-shelf transport of sediment (including "wave/current-driven" and "density-driven" processes), and

2) contrast results in a high-energy wave system (e.g., the Eel River shelf) with the results in lower-energy wave systems in the Adriatic Sea and the Gulf of Lions.

OBJECTIVES

Our main objective within EuroSTRATAFORM is to investigate sediment dispersal mechanisms at shelf water depths. We have been involved with two major experiments within the EuroSTRATAFORM framework, in the Adriatic Sea (sampling from 2000 – 2003) and in the Gulf of Lions (sampling 2004 - 2005).

In the Adriatic Sea, instrumentation placed on the Po River delta and in the Apennine Rivers region (Pescara shelf), along with seasonal water-column profiling and subsequent data analyses have allowed us to:

1) investigate the range of processes responsible for shelf transport of sediment (including "storm-driven" and "density-driven" processes), their dominant pathways (surface plume, intermediate nepheloid layer, or bottom boundary layer), their relationship to grain size and their role in shelf development;

2) provide a regional climatology of sediment transport processes (Po River delta & Apennine Rivers regions);

3) compare and contrast results in the Adriatic Sea (from two study areas: one with concurrent oceanic forcing and river discharge, and one with disconnected oceanic forcing and river discharge in time) with results from other low- and high-energy systems.

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14. ABSTRACT
The long-term goal of the sediment transport and accumulation component of Euro-STRATAFORM is to link sediment-transport processes to the formation and preservation of event beds in sediment deposits. Specifically we would like to 1) investigate the range of processes responsible for along- and off-shelf transport of sediment (including ?wave/current-driven? and ?density-driven? processes), and 2) contrast results in a high-energy wave system (e.g., the Eel River shelf) with the results in lower-energy wave systems in the Adriatic Sea and the Gulf of Lions.

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And in the Gulf of Lions (GOL), we have started to investigate the following questions:

4) Why is the shelf break a region of little to no sediment accumulation? Is sediment deposited temporarily and swept clean periodically? Or are processes persistently active to keep the shelf break clean of modern sediment? What controls the sand-mud transition on the outer shelf of the GOL?

5) Is off-shelf sediment transport a function of the shelf width, or proximity to river mouths? Are shelf-break nepheloid layers the mechanism that transports sediment off the shelf? Or are density flows active here with the cold, dense-water bottom flows a contributing factor?

6) Are the major conduits of off-shelf transport through submarine canyons? Are gravity flows common in canyons due to focusing of sediment and steep slopes? Do the winter-time cold, dense-water bottom flows contribute significantly to off-shelf transport?

APPROACH

Two study areas within the Adriatic Sea were chosen for investigation as part of EuroSTRATAFORM to provide contrast to the Eel River shelf. The *Po Delta* and the *Pescara Shelf* allow evaluation of two different end-member river systems discharging into a relatively low-energy oceanic basin. Po River discharge comes from a large drainage basin and is relatively disconnected in time from energetic conditions in the Adriatic. The sediment deposit located mainly to the south of the Po River mouth suggests dominantly alongshelf dispersal of sediment from this point source. The processes that contribute to and redistribute sediment were investigated by deploying an instrumented benthic tripod on the 12-m isobath, from January 2001 to April 2002, which collected time-series data of nearbed sediment-transport parameters. In contrast to the Po River, discharge from the Apennine rivers is highly episodic, coming from a distributed-source system of small, high-yield drainage basins. High discharge and more energetic oceanic conditions probably occur concurrently. The shelf is characterized by steep slopes and a prograding clinoform feature which suggests that sediment discharged from the rivers is likely transported rapidly across-shelf. An additional series of deployments occurred from October 2002 until May 2003, providing a third winter of time-series data at the Po River delta and offshore of the Pescara River mouth on the Apennine coastline (PASTA experiment). The Eel River is an episodic, high-yield system and floods occur contemporaneously with high-energy conditions in the ocean basin similar to the Apennine rivers. However, the dominant depositional feature is a mid-shelf mud deposit rather than a clinoform.

Physiographic and hydrodynamic complexities in the Gulf of Lions present an opportunity to investigate another combination of processes. Collaboration within the North American (NA) and European Union (EU) EuroSTRATAFORM program supports a framework to study questions relating to off-shelf transport and transport on a canyon-incised slope. The experiment in the GOL in 2004 - 2005 provided a contrasting data set to the results of both STRATAFORM (Eel River shelf and slope) and the initial investigations of EuroSTRATAFORM on the Adriatic Sea. The shelf/slope morphology in the GOL provides environmental features that enable studies of off-shelf transport such as: variable shelf width, currents influenced by topography, canyon-incised slope, broad outer shelf region, strong internal waves and cold-water bottom-plume formation. The winter 2004 – 2005 experiment was designed to study the mechanisms of off-shelf transport. These mechanisms will be evaluated from the Tet river mouth (Wheatcroft, OSU and DuMadron, Perpignan), past the inner-shelf zone of mud deposition, across the relict sands on the outer shelf, and over the shelf break to the canyon-incised slope. Our role is to investigate the off-shelf transport and canyon through the deployment of two boundary layer systems; one on the outer shelf, the other in a canyon head. The instrument locations were coordinated with P.Puig (CSIC- Barcelona) and X. DuMadron (Perpignan), as well as the multiple NA EuroSTRATAFORM participants.

WORK COMPLETED

Adriatic Sea: We maintained a boundary-layer tripod near the mouth of the Po River for a period covering three winters, and another tripod near the mouth of the Pescara River for the joint PASTA experiment. The array allowed us to examine the sediment dispersal dynamics from the mouth of the Po to south of Pescara (Fain et al., accepted), and study processes on the topset and foreset regions of the clinoform feature characteristic of this area (Puig, et al. accepted). The data is also being analyzed for studies of internal-wave dynamics in the crenulated region of the foreset (Puig, ICM and Cacchione). The UW instruments collected data to examine boundary-layer processes, sediment characteristics, and water-column currents. Analysis of this high-quality data set is still in progress and results have been published (see PUBLICATIONS) and are in the process of being published. Our focus over the past year has been on completing publication of an overall event analysis (Fain, et al., accepted), assisting with publication of other multi-investigator process papers (e.g., Puig et al., accepted), and performing analysis of the more detailed data that was collected in the Adriatic, linking the water column processes with the seabed signatures (see below).

Gulf of Lions: Off-shelf and canyon dispersal mechanisms were the goal of the Gulf of Lions experiment. We deployed two instrumented bottom-boundary layer tripods at the western end of the gulf, one on the outer edge of the shelf mud deposit and one in the head of the LaCaze-Duthiers canyon, and collected data throughout the winter of 2004-2005. These tripods were deployed in conjunction with a similar tripod and moorings in the Cap de Creus canyon (P.Puig, CSIC, Barcelona), located to the southwest of the LaCaze Duthiers canyon. Also integral to our analysis were water-column surveys collected by G.Kineke (BC) and seabed information collected by C. Nittrouer (UW) and B. Mullenbach (TAMU).

RESULTS

Adriatic Sea

Event Analysis: Analysis of sediment transport events has been completed for the long, monitoring time series on the Po River delta, as well as off the Pescara River mouth (Fain et al., in press). The sediment-transport mechanisms that contribute to and redistribute the modern sediment deposits on the western Adriatic continental shelf were evaluated utilizing data collected from two instrumented benthic tripods deployed at 12-m water depth, one in the northern Adriatic basin on the Po River subaqueous delta, and the other in the central Adriatic basin on the Pescara River shelf. Sediment-resuspension events driven by cold, northeasterly Bora winds dominate the along-shelf transport climatology at both tripod locations, but at the Po delta site, the southwesterly Scirocco wind events also play a significant role. At the Pescara shelf site, interaction between Bora wind-driven currents and the Western Adriatic Coastal Current strongly contributes to the resuspension and advection of suspended sediment. Interannual variability of the forcing mechanisms (including strength, frequency, and relative mix of Bora and Scirocco wind events) is evident in the three winters of data collected on the Po River subaqueous delta. In both types of wind events, and throughout all years of data collection, the net along-shelf sediment transport is significantly larger than the net across-shelf transport at the 12-m sites. This may be characteristic of low-energy environments, where sediment resuspension and transport occurs in such shallow water that it is not subjected to strong downwelling features characteristic of higher-energy environments.

Low and High Energy Systems: The western Adriatic coastline borders a relatively low-energy (as defined by wave energy) epicontinental sea. In this environment, sediment resuspension occurs primarily in response to winter storm events, as is the case in higher-energy environments. A major difference between these types of environments occurs in the zone of sediment resuspension, where active wave processes are significantly shallower in low-energy environments than in high-energy environments, resulting in different transport mechanisms. In lower-energy environments, transport appears to occur primarily in the along-shelf direction in water depths where wave resuspension is frequent, with little across-margin transport. This is likely due to resuspension by waves in shallow water where the Ekman layer may be thicker than the water depth. In higher energy environments, wave resuspension occurs in water depths where a distinct bottom Ekman layer can form. For example, on the western Adriatic continental shelf and the Ebro River margin, both relatively low-energy environments, the along-shelf sediment flux during winter experiments was one to two orders of magnitude greater than the across-shelf flux at 12-m water depth. In contrast, on the highly energetic northern California shelf, distinct downwelling signatures are seen at 60-m water depth where frequent storm resuspension is observed and the across-shelf sediment flux is persistently seaward during storms and of equal or greater magnitude than the alongshelf flux. This suggests that the resulting sediment deposit from fluvial sources along low-energy coastlines would be located in shallow water and linearly distributed along the coastline with little loss of sediment to offshore environments. In higher-energy environments, fluvial sediment would be distributed farther offshore with more sediment escaping the shelf environment.

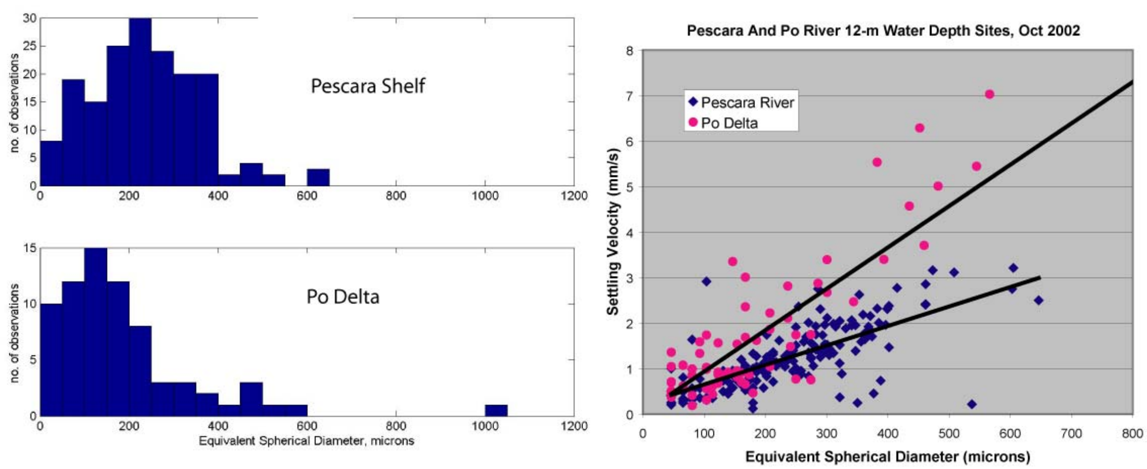

Figure 1. Grain size histogram showing number of flocs in relation to floc diameter for the two study areas in the Adriatic Sea, and relationship between size and settling velocity for those aggregates obtained through video oberservation over the same ~10 day period in October 2002. Note the difference in packaging between sediment at the Po Delta and on the Pescara River shelf.

Grain Size and Settling Velocity: The dispersal of sediment away from the Po River mouth can be largely attributed to both surface plume and bottom boundary layer (BBL) processes. In environments with larger mean waves and currents, such as on the northern California and Amazon continental shelves, the BBL sediment load is almost always larger than the surface plume load over the depositional site. A majority of the Po sediment falls out of the water column in the form of flocs inshore of the 6-m isobath (Fox et al., 2004), but there is still sediment carried in the surface plume offshore of the 6-m isobath. Analysis of the grainsize and settling velocity of sediment that is in suspension at the 12-m sites on the Po delta and Pescara shelf show distinct differences in the packaging of sediment into flocs between the two sites (Fig. 1). At the Po Delta site, particles were observed to be flocculated, but generally smaller than the flocs observed at the Pescara shelf site. But interestingly, for the same size flocs, the settling velocity is higher at the Po Delta than at the Pescara shelf (Po flocs are denser than Pescara flocs). There are a number of potential reasons for this difference, and our analysis will attempt to establish a rationale.

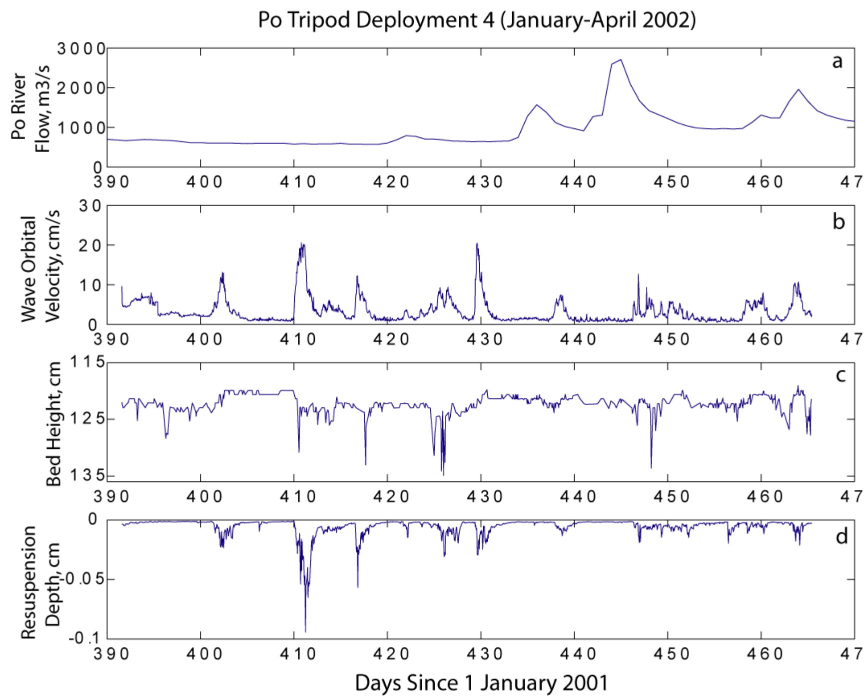

Figure 2. A preliminary example of analysis of seabed erosion/ deposition as a result of individual events. (a) shows the Po River flow, increasing in the second half of the deployment, (b) shows multiple storms increasing the wave-orbital velocity, (c) shows the response of the altimeter to the storms, and (d) shows the resuspension depth as calculated from the load of suspended-sediment concentration in the water column. Although the altimeter appears to not provide a "resuspension depth" during storms, it does indicate that sediment porosity is likely affected to depths of a few cm during storms and the difference in seabed elevation before and after storms is valid.

Seabed Changes over Event Scales: Changes in erosion and deposition of the seabed have generally been interpreted from changes in surfaces of sediment cores. This yields an understanding of long-term trends, but not an understanding of the effect of individual events. We are presently analyzing altimeter and suspended-sediment data from the Po River tripod and correlating with seabed inventories of ^{7}Be obtained from the seasonal coring at the tripod location. We are beginning to establish the connection between our water-column signals and changes observed in the seabed. Comparison between erosion and deposition from the start to the end of a deployment are comparing well with the values obtained from ^{7}Be. During storm events, the altimeter shows seabed disturbance to a few cm depths (Fig.2). This indicates that the altimeter is not providing the "resuspension depth" during storms (the resuspension depth estimated from the sediment in the water column is on the order of mms), but rather that sediment porosity is probably affected to depths of a few cm during storms. Since the porosity likely returns to pre-storm values within a few hours after the storm, the difference in seabed elevation before and after storms appears to be valid. Thus, we can evaluate the erosion or deposition resulting from individual events that would not be possible by seabed coring.

Gulf of Lions

Initial Data Interpretations: We are still in the process of quality-checking the data obtained in the winter of 2004-2005 in the Gulf of Lions. However, some simple statements about the processes controlling off-shelf transport can be made. On the outer edge of the shelf mud deposit, the strong northerly winds that blew through much of the winter period generally showed little impact on the seabed due to the narrow shelf width and resulting limited fetch at the shelf tripod site (see early part of Fig.3 a and b). This implies that although cold, dense-water formation may occur on the shelf during strong northerly winds, it will carry little sediment out to the outer shelf and canyon heads unless an additional means of resuspension exists. Only during the peak of winter when winds were strongest and larger waves appear to have propagated from other areas (January 2005, days 365 – 400 in Fig. 3) were conditions potentially sufficient to both resuspend sediment on the outer edge of the shelf deposit and transport sediment off shelf. In the canyon, it appears that down-canyon flows occurred due to many processes, not just cold, dense-water flows (Fig 3c). Six periods of down-canyon flow are identified in Fig 3c, some are bottom-intensified (A, B, D and F) while others appear to involve the entire water column within the canyon (C and E). Further work will be needed to show which periods were due to cold, dense-water formation on the shelf. However, Period D for example shows characteristic signatures of lowereded water temperature in the bottom-intensified flow that was directed down canyon. The echo intensity implies that there was sediment in this bottom flow, likely correlated with the high wave-orbital velocities on the shelf.

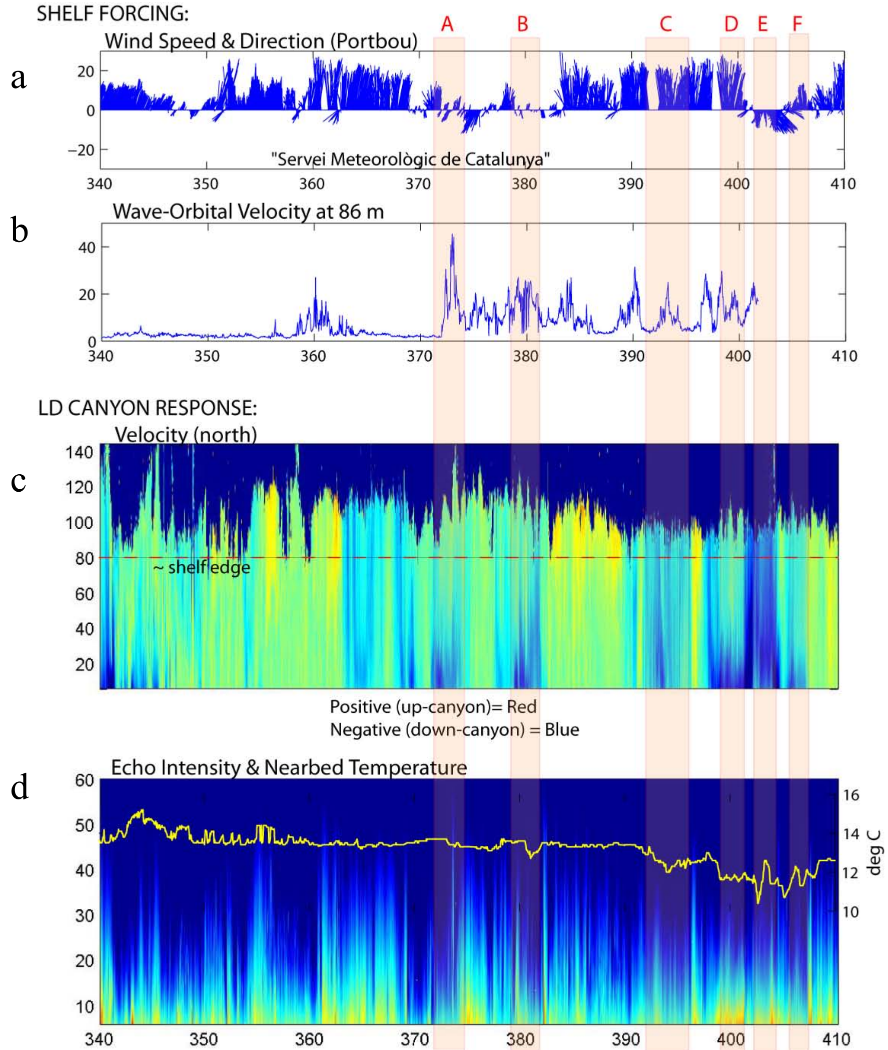

Figure 3. Gulf of Lions forcing on the western limit of the shelf deposit (winds at Portbou in a, and measured wave-orbital velocity in b) for the period between 6 Dec 2004 and 14 Feb 2005 and corresponding the Lacaze-Duthiers canyon response (ADCP currents in c and echo intensity and nearbed temperature in d). Six periods of down-canyon flow are highlighted, each due to variable mechanisms.

IMPACT/APPLICATION

The work described will allow the sediment transport community not only to extend results from previous studies, but also to gain new insights on transport processes in two relatively low-wave-energy environments. Studies near the mouth of the Po River allow investigation of transport processes where floods and storms are not necessarily concurrent in contrast to those of the Eel River shelf. The two study areas within the Adriatic provide a comparison between transport processes away from the mouth of a point source (Po Region) and at the downstream end of a multiple source system (Apennine Region). Studies in the Gulf of Lions will provide insight into off-shelf and down-canyon transport processes. Data from both experiments is and will be used to validate modeling efforts of both the physical oceanography and the sediment transport and accumulation of these differing environments.

TRANSITIONS

The EuroSTRATAFORM program is a collaborative project among many investigators. Understanding of the sediment dispersal mechanisms in both the Adriatic Sea and the Gulf of Lions is important to the overall success of this project, if we are to attain the long-term goal of linking modern transport processes to formation and preservation of strata. The data collected are being used by multiple investigators in the EuroSTRATAFORM program.

PUBLICATIONS

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Geyer, Mullenbach, Sherwood, Ogston, Kineke, Signell, Puig, Traykovski, “Downwelling dynamics of the western Adriatic Coastal Current”.

Palinkas, Nittrouer, Ogston, Miserocchi, Langone, “Modern Shelf Sedimentation Along the Apennine Coast, Adriatic Sea”

EuroSTRATAFORM, Annual meeting & workshop, Keystone, CO, July 2004.

2005 EuroSTRATAFORM Meeting:

Ogston, A. S., Lomnicky, T.D., Puig, P. “Shelf to canyon sediment dispersal in the Gulf of Lions” EuroSTRATAFORM, Annual meeting, Salamanca, Spain, October 2005.

Sherwood, C.R., Harris, C.K., Ogston, A., Signell, R.P., Warner, J.C., Wheatcroft, R.A. and Wiberg, P.L., “Sediment Transport Along the Apennine Margin” EuroSTRATAFORM, Annual meeting, Salamanca, Spain, October 2005.